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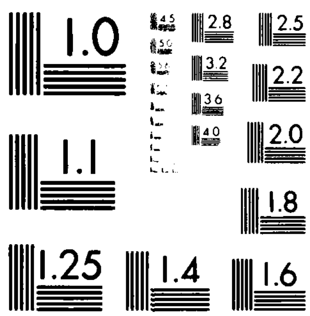

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IIT Research Institute
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Chicago, Illinois 60616

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19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

- EMP Shielding
- Shield Design
- Shielding Effectiveness
- Test Bed Facility

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

A shielded enclosure Test Bed Facility is recommended for obtaining data relating EMP shield design to the internal fields and internal cable coupling. The facility should accommodate a shielded enclosure approximately 10 ft high x 20 ft wide x 50 ft long, to study a variety of shield design parameters, e.g., shield panel material and thickness, joint construction, and penetrant configurations. It should provide for excitation by CW injected current and a radiated pulse. Several analytical and laboratory tasks are recommended in support of the test bed experiments.

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SUMMARY

The purpose of this task was to determine whether it is advisable for the Government to build a shielded enclosure Test Bed Facility to obtain additional data useful for the design and testing of shielded C^3 facilities.

The approach taken in carrying out this study was to determine what types of shielding information are required, and whether this information might be more readily obtainable from other sources such as laboratory tests or tests on operational shielded C^3 facilities.

It was concluded that a dedicated Test Bed Facility is required for obtaining the following types of information:

- Relationships between the shield design and construction parameters and the fields within the shielded enclosure, as well as the internal coupling to interconnecting equipment cables;
- Relatively simple procedures for measuring the shielding effectiveness of an enclosure both for initial certification and for periodic or continuous monitoring of an operational facility;
- Effects of shield magnetic saturation for a ferromagnetic shield.

The Test Bed Facility should accommodate a shielded enclosure approximately 10 ft. high x 20 ft. wide x 50 ft. long with a variety of shield design and construction parameters such as shield panel material and thickness, joint and/or seam bonding construction, and various penetration control configurations. It should have the capability for both CW injected current excitation and radiated pulse excitation, and appropriate sensors and signal processing equipment for data collection.

Test Bed Facility experiments are recommended to: map exterior and interior surface current densities and internal fields, measure internal cable coupling, develop simplified procedures for measuring shielding effectiveness, and investigate the effects of magnetic saturation on ferromagnetic shielding performance.

The following additional tasks are recommended in support of the test bed investigations: small-scale model laboratory tests to determine the distribution of external surface currents coupled to the shield and the effect of various facility grounding configurations, development of simple analytical models relating shield design and internal fields and coupling, simplified procedures for measuring shielding effectiveness, effects of shield magnetic saturation, and evaluation of alternative definitions of shielding effectiveness applicable to a wide variety of conditions.

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SECTION 1

INTRODUCTION

This is the Final Report on Task V of Contract DNA 001-79-C-0205. The objective of this task was to determine if it is in the Government's best interest to construct and operate a large-scale EMP shielding test bed facility to obtain shielding effectiveness data for enclosures having a variety of shield parameters and construction options.

1.1 GENERAL

In the past, designers of EMP shields for large structures, such as a C^3 facility, have taken a conservative worst-case approach to specifying the materials, construction methods, and penetration control techniques to be used in achieving a desired level of shielding effectiveness. More often than not, this approach resulted in the design of the familiar continuously welded, low-carbon steel envelope shield with special treatment of all penetrations through the shield. The general consensus within the EMP community is that such a shield design will provide a shielding effectiveness of approximately 80 to 100 dB which reduces the interior field levels to values which, for the most part, will not damage or upset internal equipment. Consequently, with such a shield a minimal amount of protection, if any, at the equipment level is required to mitigate potential EMP effects.

Experience has shown that the cost of such a shield is quite high. This fact leads one to consider alternative ways to design and/or construct EMP shields for these large facility structures. However, in so doing, one is faced with many unanswered questions regarding such fundamental issues as:

1. What is meant when one specifies a shielding effectiveness of 100 dB? or 80 dB, or 60 dB? What is the significance of a single specified shielding value when the internal fields can be expected to vary over some range due to apertures, corners, and possibly resonances within the enclosure?
2. What is the significance of the shielding effectiveness, expressed for fields measured with CW signals, in relation to the EMP transient coupling to interior cables?
3. What is the impact of available shield design and construction alternatives on the overall shielding effectiveness of the shield?

Issues such as these have led to the consideration of developing an EMP Shielding Test Bed Facility to perform investigations that might answer these and other basic questions.

The purpose of this task of the present contract was to consider if it is advisable for the Government to construct such a Test Bed Facility and, if so, to ascertain the types of investigations that should be conducted with it. This report presents the results of that study.

1.2 ORGANIZATION OF THE REPORT

Section 2 of the report discusses the need for five types of shielding data:

- The relationship between shield design and internal fields;
- A meaningful definition of shielding effectiveness;
- The relationship between shield design and internal coupling;
- Simplified procedures for measuring shielding effectiveness; and
- Effects of shield magnetic saturation.

For each type of experimental data required, the alternative ways of obtaining the data are then considered.

Section 3 discusses four proposed investigations for which a Test Bed Facility is required, and Section 4 describes three other tasks -- partly experimental and partly analytical -- in support of the proposed Test Bed investigations.

Section 5 presents the conclusions and recommendations.

SECTION 2

TYPES OF SHIELDING DATA NEEDED

2.1 INTRODUCTION

The Government, in procuring an EMP shield for a C^3 facility, has two major options: (1) specifying in detail all important design and construction features of the shield, and accepting the resulting shielding performance; or (2) specifying in detail all important performance characteristics the shield must provide, leaving the design to the contractor. It might be irrelevant which of these two options is chosen if both the principles for optimum shield design and the appropriate methods for specifying and measuring shield performance were well established. At present, however, information both for shield design and for shield performance specification and measurement is inadequate to assure satisfactory minimum-cost shield design for given EMP protection requirements. In fact, even the presently used definitions of shielding effectiveness are far from satisfactory as they provide only very limited information regarding the leakage fields within the interior of the enclosure.

While it is important to know how to design a shield to provide a specified level of shielding effectiveness when the enclosure is empty, it is even more important to be able to characterize the internal coupling of the leakage fields to the equipment racks and interconnecting cables within the enclosure. Thus, procedures need to be developed to relate the expected coupling and interaction to equipments/cabling within the shield to quantitative measures of the shield performance effectiveness, namely, its various alternative design and construction parameters.

For the EMP threat, shielding against low-frequency magnetic fields is extremely important, and a ferromagnetic material such as steel is especially useful for this purpose. Such a material, however, can become magnetically saturated, resulting in a partial loss of shielding effectiveness. Experiments are needed to provide data on the effects of saturation and how they must be taken into account when using a shield in mitigating against the EMP threat.

Accordingly, it is essential that sufficient engineering data be developed to provide shield design guidelines and procedures, as well as appropriate procedures for specifying and measuring shielding effectiveness. This section of the report considers the types of data required and the alternative methods of obtaining the data.

2.2 RELATIONSHIP BETWEEN SHIELD DESIGN AND INTERNAL FIELDS

Usually the overall objective of C^3 shield design is the determination of the lowest cost shield which is capable of providing a specified level of shielding protection for the facility. Some shield cost information is available.[1] A more fundamental requirement, however, is the need to determine the required, or permissible, design features which must, or may be, incorporated in a shield intended to provide the specified shielding performance. This implies the need for sufficiently accurate procedures for calculating (predicting) the shielding level achievable for any desired candidate shield designs.

The predictive techniques need to be based on and validated by internal field measurements on a reasonably representative set of shielding design and construction configurations. These must include various shielding materials, thicknesses, panel joining techniques and procedures, aperture control methods, and treatments of penetrations. The effect of various facility grounding techniques should also be included in this parameter investigation.

Types of shielding materials should include:

- Hot rolled steel sheets
- Galvanized steel sheets
- Copper sheets
- Aluminum sheets

Thicknesses should include values from the minimum which may be capable of providing significant shielding while possessing adequate mechanical integrity, up to the maximum thickness which could be required for providing what might be considered the maximum degree of shielding which may be needed in a practical situation. Thus, materials might range from metal foil on a base material (e.g., wood or drywall) to moderately heavy gauge steel sheets (e.g., 14 ga).

Methods for fastening and/or bonding the adjoining edges of the metal foil or sheets should include, where appropriate: conductive metal tape, welding, soldering, riveting (including powder driven pins), and arc spraying of metal. Variations in implementation techniques of interest include seam overlap, bolt (or rivet) spacing, weld or solder continuity requirements, and arc sprayed metal thickness and seam width.

Another area of shielding which requires additional data is in relation to shield penetrations such as pipes, doors, cables, air vents, etc. Taken one at a time, the techniques for handling these penetrants so as to achieve and/or preserve the "classic" 100-120 dB EMP shield are well established, i.e., 360° welded bond, single point of entry, waveguide beyond cut-off, etc. However, the question arises as to how far it may be possible to relax these procedures for a shield requiring only 60 or only 40 dB shielding. Experimental data is needed to determine what penetration treatments are adequate to provide specified lesser degrees of shielding.

For the types of data requirements indicated above, substantial flexibility must be available in the shielded facility on which the tests are performed. Most importantly, it must be possible to readily change the nature of the shield itself. Such tests cannot be performed on an operational C^3 facility.

Furthermore, the extensive field mapping of the interior of the shielded enclosure requires a reasonably large enclosure so as to accommodate test personnel and instrumentation, as well as certain important shield features such as numerous metal panels and joints and a shielded door. A minimum size required would be approximately 10 ft high x 20 ft. wide x 40 or 50 ft. long. Thus, the required enclosure, including EMP excitation, is larger than could readily be accommodated as a laboratory facility. A special, dedicated test bed facility, therefore, appears to be required.

Although the test bed facility would provide extensive measured data for a variety of shield conditions, it can be expected that there will be requirements to interpret and/or extrapolate this data base to shield designs for larger enclosures having more seams, penetrations, etc. For this purpose, it appears desirable to develop simple analytical models that relate baseline test bed data to structures of different size, number or penetrations, etc. This work is proposed as a supporting task.

The recommended test bed measurements would probably best be performed on shielded enclosures excited both by an incident radiated field and current injected onto the exterior of the enclosure. In order to guide these test bed experiments, preliminary tests could be performed on a small-scale model to determine external surface currents on an enclosure under various excitations. These tests could also include investigation of the effects of various external grounding configurations. These supporting tests could probably be performed in a laboratory facility (e.g., a sand box facility) rather than in the test bed facility itself.

2.3 MEANINGFUL DEFINITION OF SHIELDING EFFECTIVENESS

A shielded C^3 facility can receive HAEMP excitation by two predominant modes: (1) a radiated field, incident on the enclosure; and (2) currents collected by long conducting penetrants and injected onto the shield. The first mode is always present and important; the importance of the second mode depends on the length of the penetrants and their relative orientation. The incident radiated field can be considered to be a plane wave, and thus has both electric and magnetic field components, and a wave impedance of 377 ohms. The injected current directly produces an external surface current on the shield, resulting in a proportional magnetic field, and also in a surface electric field due to the finite conductivity of the shield.

The present definitions of shielding effectiveness are based on the ratio of two measured fields. These fields, of course, are dependent on both the frequency and the spatial location of the point where the shielding level is specified. For the magnetic field:

$$SE = 20 \log_{10} \frac{H_o}{H_i} \text{ ; and}$$

for the electric field:

$$SE = 20 \log_{10} \frac{E_o}{E_i} \text{ .}$$

The terms H_i and E_i are the fields (at specified locations) within the enclosure, and H_o and E_o are the corresponding fields (at the same locations) in the absence of the enclosure.

As discussed further in Section 2.4, an important shortcoming of the present method of specifying shielding effectiveness is the measurement and specification using CW at a very limited number of frequencies and in a small number of limited regions of the shield. In particular, the measurements at only a few locations -- and those primarily very close to the enclosure walls -- do not portray the magnitude of field throughout the interior of the enclosure, where equipment racks and cables may be located.

One possible method for describing shielding effectiveness of an enclosure is by use of conceptual iso-shielding surfaces within the enclosure. These contours, shown in a simplified way in Figure 1, indicate the level of shielding effectiveness. Thus for an external field of any given magnitude incident on the enclosure, the contours show the shielding effectiveness, and hence the field levels, throughout the enclosure. The shapes of the contours would show the effects of wall currents, current concentrations near the corners of the enclosure, effects of apertures, and enclosure resonance.

Data for any one frequency could provide a set of contours as shown in Figure 1. It would be desirable to obtain such a plot at enough frequencies within the 10 kHz to 100 MHz band so as to be able to characterize any significant variations of shielding effectiveness throughout this EMP spectral region.

Another possible way of portraying shielding effectiveness is on a statistical basis. For example, at any one measurement frequency, field measurement data (and hence shielding effectiveness measurement data) taken at equal spatial increments throughout the

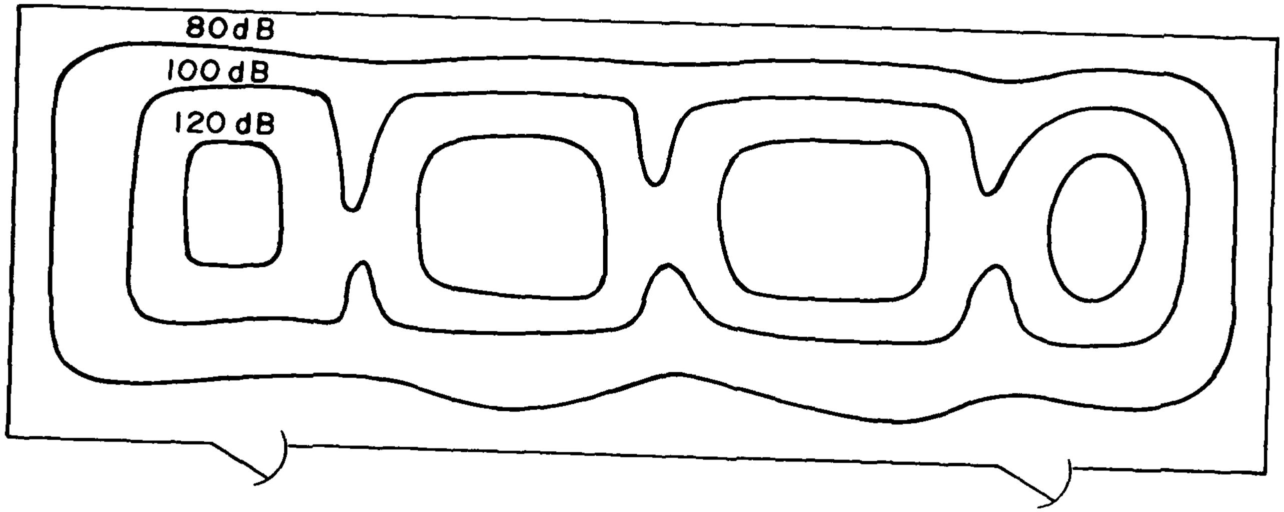


Figure 1. CONCEPTUAL ISO-SHIELDING SURFACES WITHIN A SHIELDED ENCLOSURE

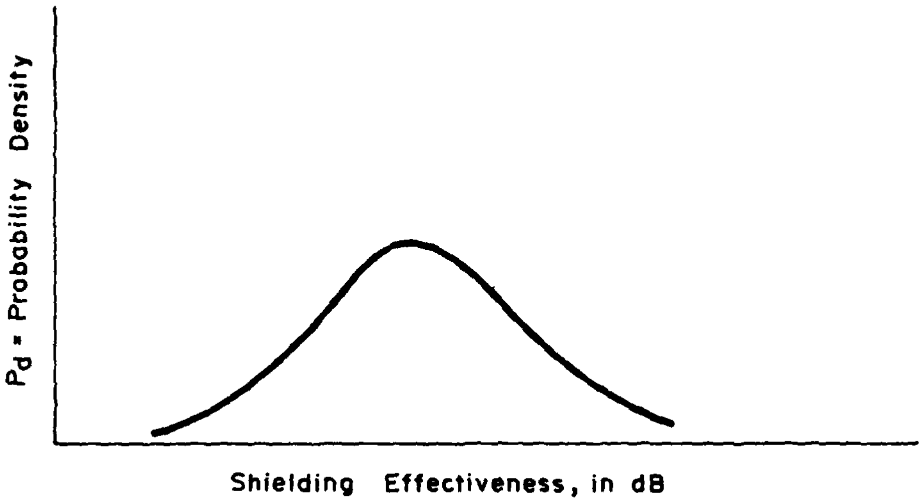
enclosure could be grouped statistically and the results portrayed by a probability density function, as shown in Figure 2(a). Thus, the statistical distribution of shielding effectiveness -- but not the spatial distribution -- would be specified for the enclosure. If the distribution followed some known distribution, e.g., Gaussian, the results could most simply be stated by a mean value and standard deviation of shielding effectiveness.

It would be expected that the peripheral region of the enclosure (near the walls and corners), would generally have lower values of shielding effectiveness than the more central region. If this is the case, the possible exclusion of a guard region of space (e.g., one meter wide) near all walls, would be expected to produce statistics more nearly like those in Figure 2(b). Here the mean value of shielding effectiveness is increased, and the standard deviation reduced somewhat. The area under the curve and to the right of any selected (desired) value of shielding effectiveness represents the probability that the shielding effectiveness at any point within that selected portion of the enclosure exceeds the desired value.

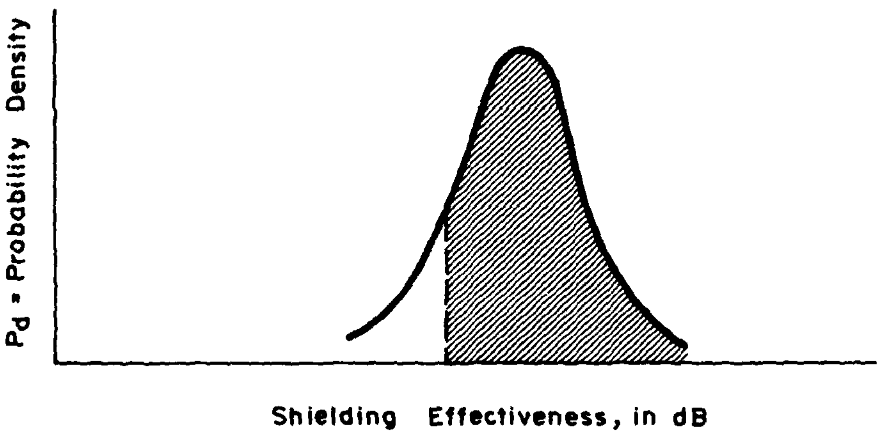
While, in principle, such a statistical distribution of shielding effectiveness could be determined for every frequency at which measurements are made in the EMP spectral band, such a quantity of data would be excessive and unusable. It would be necessary to determine a procedure for using data at specific, worst-case frequencies, or averaging the data for all frequencies.

All present definitions of shielding effectiveness utilize a ratio of field levels at specific frequencies, with data taken on a CW basis. Since EMP is a wideband transient phenomenon, a definition of shielding effectiveness is needed indicative of the pulse nature of the waveform. If CW data (both amplitude and phase) were measured over the entire EMP spectral region, the transfer function of the shield would be known. It would therefore be possible to calculate or synthesize, the pulse waveform within the enclosure for an incident pulse of any arbitrary waveform. It may then be possible and meaningful to define shielding effectiveness on a pulse basis, e.g., as the ratio of the peak values of the incident field and the internal field (at some point, or possibly statistically).

A separate definition is required for the shielding effectiveness associated with current injected directly onto the shield exterior from long external conductors. Here, a ratio of internal field to external current may be more appropriate. A measure of shielding effectiveness used to characterize cable shields, i.e., the surface transfer impedance method, may be more appropriate. Also, the use of a ratio of external surface currents to interior surface currents may be useful.



a) P_d Based On Fields Throughout Enclosure



b) P_d Based On Fields Within A Selected Portion Of Enclosure

Figure 2. STATISTICAL REPRESENTATION OF SHIELDING EFFECTIVENESS WITHIN AN ENCLOSURE

The consideration of various appropriate definitions of shielding effectiveness is seen primarily as an analytical task accompanying and following the extensive collection of internal field data for the various shield designs.

2.4 RELATIONSHIP BETWEEN SHIELD DESIGN AND INTERNAL COUPLING

As discussed earlier, a test bed facility and an analytical program are required (1) to establish definitive measures of shielding effectiveness for large shielded C^3 structures, and (2) to relate changes in those shielding effectiveness measures as a function of alternative shield design and construction techniques. These discussions pertained to the field measurements and shielding effectiveness of an empty enclosure, where the interior fields can be mapped in detail.

In addition, there is a requirement to relate the effect of shield design/construction parameter variations on the coupling of EMP energy to equipment racks and cables inside the shielded enclosure since it is the voltages and currents induced on the cables which result in possible circuit malfunction or damage. Experiments are needed to measure the induced bulk cable currents in equipment rack and cable mockups arranged in both representative and worst-case layouts within shielded enclosures of different design/constructions having various levels of shielding effectiveness, e.g., 40, 60, 80, and 100 dB. The experiment should permit placing the cables various distances from exterior walls, corners of the building, and possibly various heights above the floor. Thus, the purpose of the tests is to determine any possible basis for tradeoffs in shielding level and cable length and routing, including the observance of any cable exclusion regions where leakage fields are high.

Clearly, such experiments cannot be performed in an operational C^3 facility, nor in the laboratory where only small shielded enclosures with fixed construction are available. Thus, a test bed facility of adequate size and versatility is required for these internal coupling tests.

2.5 SIMPLIFIED PROCEDURES FOR MEASURING SHIELDING EFFECTIVENESS

It is desired to be able to characterize the shielding effectiveness of a C^3 facility for threat level EMP excitation of the same type which an operational facility could experience. To the extent that shield behavior is linear, simulators providing sub-threat excitation can be used, with results extrapolated to the threat level case. The use of pulse simulators to test a facility is time consuming and expensive, not only because of the tests themselves, but because of the lengthy set-up time. Furthermore, pulse simulators are large and costly, and are therefore relatively uncommon. As a result, most shielding effectiveness tests for enclosures use CW techniques. The CW methods used have the advantage of smaller and less expensive equipment, and shorter set-up and testing times. Unfortunately, they do not provide an indication of the shield leakage for the transient case.

The present definitions of shielding effectiveness and test methods and procedures are based on CW insertion loss measurements (attenuation) for a very limited number of frequencies and field characteristics. They are based on the ratio of (1) the free field (E or H) which would exist at a given point in the absence of the enclosure, to (2) the field which exists at the same point, surrounded by the enclosure.

Most shielding effectiveness testing is performed according to Specification MIL-STD-285.[2] These tests are performed using, for example, two small loops, at one frequency in the 150 kHz - 200 kHz range; monopole or dipole antennas at 200 kHz, 1 MHz, and 18 MHz; and resonant antennas radiating plane waves at 400 MHz. In each case one (radiating) antenna is placed outside the shield, a specified distance from the surface (e.g., 1 foot), and the second (receiving) antenna is placed a similar distance from the inner surface, at a point directly opposite from the radiating antenna. Thus in all cases only local excitation of the shield is utilized, i.e., only a very limited portion of the shield is illuminated at a given time. Therefore, this method can provide an indication of local shielding effectiveness in the region of an individual shield aperture or defect (e.g., poor seam, defective door gasketing, etc.), but does not provide an indication of simultaneous leakage from a number of such features distributed over the surface of the shield. A disadvantage of the method is the requirement for coordinating the positions of the two antennas on both sides of the shield for each test point. An important shortcoming is that since only limited selected areas of the shield are illuminated, unsuspected shield defects may not be detected if measurements are not made in those particular regions. A further limitation is the requirement for access to both sides of the shield in the region where a measurement is required, thus preventing measurements on inaccessible surfaces such as the floor. Another restriction is that the measurement at a few spot frequencies and limited antenna locations provides virtually no chance to discover possible enclosure resonances, which could produce at some locations, fields significantly stronger than those at the measurement points chosen.

IEEE Standard 299[3] for measuring the shielding effectiveness of shielding enclosures also specifies the use of loops, dipoles, and microwave horns and spot frequency insertion loss measurements, similar to MIL-STD-285. However, IEEE 299 also includes a test using a large single-turn loop, oriented diagonally, around the entire shielded enclosure. This test, for low frequencies (10 kHz - 100 kHz) attempts to excite currents in all the exterior faces of the enclosure. The receiving antenna (small loop) is positioned at the center of the enclosure. This test has the advantage that the large loop tends to cause currents to flow across all seams of the enclosure. Thus one measurement is sufficient at one frequency. Measurement repeatability is also improved over the small-loop method since the position of the transmitting loop remains fixed relative to the enclosure.

The disadvantages are: (1) the test set-up is complex and would be difficult to implement for different shapes of enclosures; (2) frequency range is limited since at high frequencies the high loop impedance produces a mismatch with the signal source, thus limiting the excitation current; (3) the orientation of the tilted loop does not allow a strong field penetration through the floor and ceiling joints.[4]

Suitable procedures for measuring shielding effectiveness are required for two purposes: (1) certifying that a new shielded facility provides the required degree of shielding; and (2) providing periodic, or even continuous measurement of shielding effectiveness throughout the lifetime of the facility. To be suitable the procedure must be relatively simple to employ and reasonable in terms of cost; it must provide a measure of the actual shielding effectiveness.

To achieve these goals for certification testing of a new C^3 shielded facility, special features may need to be built into the facility at the time the facility is constructed. Possible examples are the incorporation of terminals or connectors for directly driving the facility, or built-in test loops for exciting the facility.

In terms of life cycle monitoring to identify degradation of the shielding effectiveness of the facility, much simpler procedures may be adequate. In this case, all that is needed is comparison data, providing fault location is not a simultaneous requirement. The provisions incorporated for the certification testing could be used here also. The amount and type of data could be reduced, however. For example, if a set of base line data (i.e., measurements at identified locations and frequencies) were obtained at the time the facility was constructed, these could be compared to subsequent tests at the same locations and frequencies periodically in the future. The test locations and frequencies would have to be selected such that the tests would not interfere with C^3 operations and also so that the results would be relatively insensitive to changes in equipment installations internal to the facility. This last point is important since the internal equipment configuration may significantly alter the standing waves (field distribution) inside the facility.

In order to develop a suitable test procedure which can be used for measuring the shielding effectiveness of a shielded C^3 facility, it is necessary to evaluate various candidate test procedures on a shielded facility which possesses shielding characteristics representative of both new and operational shielded C^3 facilities. Thus, the test procedures must be developed and evaluated in a facility which has, or can be designed or modified to have, various types of typical apertures, typical seams and seam defects, and typical (or simulated) internal equipment layouts. Furthermore, the facility must be of a size somewhat comparable to a C^3 facility in order to consider adequately the spatial effects within the enclosure (e.g., resonances), it must be amenable to the addition and use of experimental excitation methods (appendages or loops), and it must not have important experimental limitations due to conflicting usages.

The customary room-sized shielded enclosures are not adequate for this purpose because of their small size and their generally predetermined design and construction parameters. An operational shielded C^3 facility is unsuitable because of its fixed construction and its need to function without the operational interference certain to result from attempts to modify shield seams or apertures or to experiment with various equipment layouts. An even more serious problem may be the inability to add desired auxiliary test devices, such as wire loops around the facility in each of the three orthogonal directions. It is for these reasons that an experimental test bed facility is recommended for use in developing suitable procedures for measuring shielding effectiveness.

2.6 EFFECTS OF SHIELD MAGNETIC SATURATION

For a shield constructed of non-ferromagnetic material (e.g., copper, aluminum, or brass), the shielding effectiveness is a constant, independent of the excitation level. However, for a ferromagnetic shield such as low-carbon annealed steel or galvanized steel sheets, shielding behavior will be nonlinear for excitation exceeding a level where magnetic saturation begins to occur. While the onset of saturation occurs gradually, an applied magnetic field of 2 Oersteds, or 160 amperes/meter is a representative field level where hot-rolled, low-carbon steel begins to saturate. Magnetic saturation, in general, causes a reduction of shielding effectiveness. The extent and effects of saturation depend on the type of ferromagnetic shield material, shield thickness, EMP excitation (magnitude and duration), localized regions of current concentrations, and possibly other factors.

For an EMP threat consisting of a plane wave with an electric field strength of 50 kV/m, the incident magnetic field is 133 A/m. The total magnetic field on the surface of a large (infinite) conducting sheet would be twice that value, or 266 A/m. For a box-shaped shield, such as would be used for room or an entire C^3 facility, the current concentrations, and hence the total magnetic field at the corners of the shield may be two orders of magnitude above the value calculated for an infinite planar sheet. Thus, saturation could occur from the incident field.

Also, long conductors attached to the shield can cause high pulse currents to be injected directly onto the shield. Peak currents of perhaps tens of thousands of amperes can cause shield surface current densities, and hence magnetic intensities, which again are orders of magnitude above the saturation value for steel.

Since magnetic saturation causes nonlinear behavior of the shield, it would be desirable to test the shield for saturation effects using excitation levels up to the maximum threat. Furthermore, testing must be done with a realistic pulse excitation, since the magnitude and duration of the waveform are important in determining the depth to which saturation occurs, and whether the saturated region penetrates the entire thickness of the shield material. Another reason why pulse excitation is required, rather than low-level CW testing and use of the transfer-function method for synthesizing the pulse response, is that the latter procedure is not valid where the behavior is not linear.

The depth of shield saturation depends on the time integral of the shield surface current density (or magnetic intensity). Thus, saturation might occur for high-level short-duration transients such as those resulting from an incident HAEMP radiated wave, or for lower intensity but longer-duration transients such as those due to the current collected by long conductor penetrants and partially injected onto the shield. Therefore, data are required for two types of conditions -- radiated field and injected current -- with realistic threat waveforms and magnitudes.

Analytical work[5,6] has been done to calculate the effect of magnetic saturation on the propagation of a pulse through a flat sheet of infinite extent. Both experimental work and analytical modeling are required to extend the results to the case of saturation fields over a box-like shield.

Due to the nature of the experiments, the tests could not be performed on an operational C^3 facility. Neither could the tests be performed on a small conducting box in a laboratory. The enclosure must be large enough to accommodate test sensors and personnel within the interior. Consequently, a structure at least room-size is required, and one more nearly approximating the size of a C^3 facility would be desirable.

Perhaps the most compelling reason for requiring approximately a full-scale structure is that a small-scale model may produce misleading results. In order to produce appropriate current distribution on a small-scale structure, the waveform should also be correspondingly scaled (shortened). However, shortening the waveform will affect the time integral of the shield surface current density, and therefore will affect the depth to which the saturation region penetrates the shield. Thus, a fairly large shielded enclosure, such as the contemplated test bed facility, is needed for the investigation of saturation.

2.7 SUMMARY AND CONCLUSIONS

Based on the preceding discussion, it is concluded that a shielded enclosure test bed facility is needed for obtaining data to establish:

- Relationship between various shield design and construction techniques/parameters and the resulting shielding effectiveness of a structure;

- The effects of shield design and/or construction parameter variations on the internal coupling to equipment racks and interconnecting cables within an enclosure;
- Simplified procedures for measuring shielding effectiveness;
- Effects of shield magnetic saturation.

In addition to the test bed experimental work suggested, several supporting tasks are recommended:

- Laboratory tests on a small-scale model of a shielded enclosure (metal box) to measure the distribution of external surface currents;
- Development of simple analytical models for interpreting the experimental results and extending them to other related shield designs;
- Consideration of appropriate definitions of shielding effectiveness.

The proposed test bed experiments are discussed further in Section 3, and the supporting tasks are discussed in Section 4.

SECTION 3

PROPOSED TEST BED INVESTIGATIONS

As discussed in Section 2, a test bed facility is necessary for developing several types of information regarding the shielding characteristics of enclosures for shielding C^3 facilities. This section of the report describes specific test bed experiments and investigations proposed for obtaining the required data.

3.1 RELATE SHIELD DESIGN AND INTERNAL FIELDS

The primary purpose of this test is the measurement of the internal fields in a shielded enclosure, or enclosures, having several different shield constructional variations including different seam types and apertures.

A shielded box-like enclosure approximately 10 ft. high x 20 ft. wide x 50 ft. long is recommended. Measurements would include:

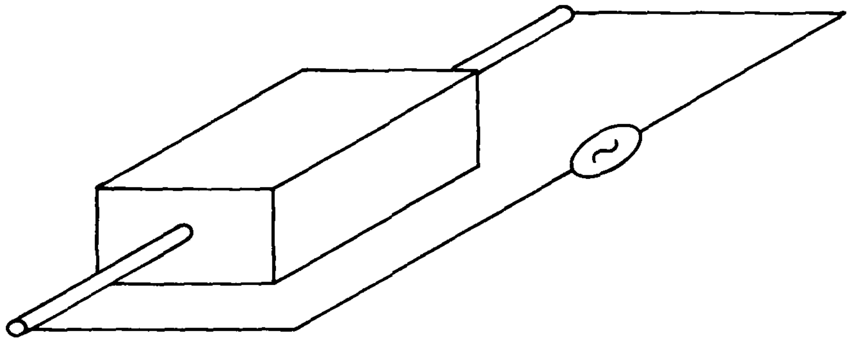
- Exterior surface current density on the five accessible external surfaces;
- Interior surface current density on all six internal surfaces;
- Magnetic field throughout the interior of the enclosure;
- Electric field throughout the interior of the enclosure.

The enclosure size recommended is intended to be large enough to be representative of a real world enclosure without being too large or costly. The enclosure must be large enough to accommodate test personnel, a personnel entry door, and a number of wall, floor, and ceiling panel joints and penetrations. It also must provide freedom in measuring the variations of the internal fields as a function of distance from apertures, and in regard to room resonance.

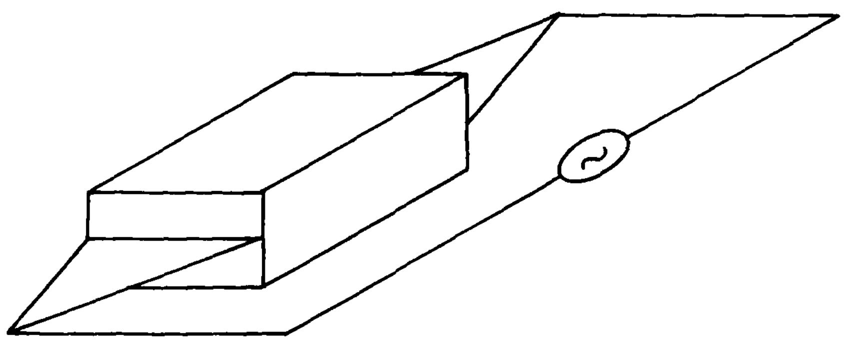
As shown in Figure 3, CW current would be injected onto the shielded enclosure by means of large metal rods or tabs welded to the ends of the enclosure. Exterior surface current density would be measured at a grid-like array of points approximately one meter apart on each of the long surfaces (top and two sides). Interior surface currents would be measured on all six surfaces. The two orthogonal components would be measured at each point.

The magnetic field would be measured on a cubic-lattice-like array of points, approximately one meter apart within the interior of the enclosure. In this case, three orthogonal components must be measured at each point.

A total of approximately 15 experiments are suggested. These could include about 10 experiments to investigate variations in seam construction and possible seam direction.



a) Simulation Of Current Injection By Single Penetrant



b) Simulation Of Current Injection By Multiple Penetrants

Figure 3. TWO POSSIBLE ELECTRODE CONFIGURATIONS FOR CURRENT INJECTION ONTO SHIELD

As examples, tests might include steel panels with 100% welded seams, and as an extreme, 50% welded seams. Also, it would be of interest to perform several experiments using galvanized steel sheets fastened by powder-driven pins or rivets. Tests should be performed with various amounts of arc-sprayed zinc along the seams, ranging from no zinc up to some reasonable maximum amount. In general, it is suggested that initially the tests be performed on shields having approximately the lowest levels of shielding effectiveness of interest, followed later by tests on shields expected to provide greater shielding. Performing the tests initially on shields having the lower levels of shielding has two advantages. First, for a given excitation level, signals will be stronger, easing the sensitivity problem of the sensors and other instrumentation. Or, conversely, for a given magnitude of internal field, initial testing of lower quality shields permits use of lower levels of excitation, thus initially minimizing the possibility of magnetic saturation (for steel shields). The second advantage is that data will become available earlier on what are probably the least costly shields.

In addition to performing tests with various shield designs, measurements should also be made for several penetrant configurations.

The high levels of shielding to be investigated will result in low levels of internal surface currents and magnetic fields, requiring sensitive instrumentation for those measurements. For this reason, a narrowband CW system is required.

Since it is desirable to obtain data which could permit calculation of the interior pulsed signal which would be expected for any arbitrary injected current pulse, it is necessary to measure the transfer functions (amplitude and phase) over the frequency band of interest (10 kHz to 100 MHz) at each spatial point chosen. Laboratory instrumentation to perform this type of measurement has been described.[7] The transmitter is driven by a frequency synthesizer which is sequentially stepped over the required frequency band by a programmer. For the present application, the transmitter output would be applied to the shield as shown in Figure 3. Two signals would need to be supplied to the receiver: (1) a reference current signal at the test frequency, (2) a local-oscillator signal. For measurements within the enclosure these two required signals could be supplied to the receiver via two dielectric waveguides. The local-oscillator signal could be transmitted directly, while the reference signal at the test frequency would first need to be put on a carrier.

The coherent receiver would provide amplitude and phase data at each test frequency, and this data would be digitized and recorded on magnetic tape along with information for frequency, spatial location, and component direction.

The use of excitation by CW current injection rather than pulse current injection is recommended due to the inherently poorer sensitivity of the wideband sensor instrumentation needed for pulse reception. For example, if a pulse were used, the sensor would be a $\dot{B}$ free-field sensor followed by a wideband (200 MHz) signal amplifier and digitizer, e.g., Tektronix 7A16P and 7912AD. The required input signal to the amplifier is a few millivolts. For a sensor equivalent area of 10^{-2} m^2 and a shielding level of 100 dB, a peak injected pulse current exceeding 10^6 amperes would be required.

If CW is used the receiver can be narrowband, consistent with transmitter and receiver frequency accuracy and stability. If a 10 Hz bandwidth is achievable, receiver sensitivity would be approximately 10^{-9} volt, requiring an injected CW current of the order of 10 amperes.

Use of CW, with measurement of amplitude and phase over the frequency band of interest, characterizes the shield transfer function and allows calculation of the transient within the enclosure for any arbitrary current waveform injected onto the shield in the same manner.

Use of current injection rather than radiation was chosen for two reasons: (1) the difficulty of achieving efficient radiation at low frequencies (e.g., as low as 10 kHz); and (2) the ability to provide a reasonably controlled current flow over most of the enclosure using injection, thus providing any desired current distribution.

3.2 RELATE SHIELD DESIGN AND INTERNAL COUPLING*

The purpose of this test is the measurement of the expected typical and worst case voltages and currents which can be induced in cables which interconnect equipment racks in a shielded facility. Therefore, mockups of equipment racks, with interconnecting cables, would be installed in a test-bed facility shielded enclosure. The enclosure would be excited with CW current injected onto the shield as proposed for the tests discussed in Section 3.1, and also with a pulsed radiated field incident on the enclosure.

Use of CW excitation, as proposed for the tests to relate shield design and the internal fields, will provide an opportunity to correlate the internal fields and the voltages induced in the cables. The CW coupling tests would be relatively brief compared with the mapping of the internal fields; they would be performed using the same excitation; and they could be performed either immediately prior to or immediately after the field mapping tests.

Use of pulse excitation would provide a direct measurement of the peak voltage and current induced in any given cable circuit.

*Many of the ideas presented here were proposed earlier by SRI International.[8]

Cable loops might include the largest possible horizontal loop which can be formed within the enclosure, or several smaller loops. The horizontal loops could be positioned at different heights above the floor to ascertain any possible advantage of locating interconnecting cables away from the floor.

Other possible test circuits might include a wire connection between opposite faces of the enclosure, e.g., lengthwise, widthwise, or ceiling-to-floor.

The pulse tests can provide a direct measurement of the peak voltage which could be induced in an operational cable (to the extent that the cable mockup simulates an actual cable layout). The CW tests can probably provide more insight into the coupling problem and, additionally are expected to be useful in the quest for relatively simple, but appropriate shielding measurement procedures as discussed in the following section.

3.3 DEVELOP SIMPLIFIED PROCEDURES FOR MEASURING SHIELDING EFFECTIVENESS

The purpose of the experiments and measurements proposed in Sections 3.1, 3.2, and 3.4 is to obtain data regarding the degree of shielding achievable with various shield construction techniques and parameters. Those proposed measurements are detailed and are intended as experiments to be conducted on the test-bed facility.

In addition, there is a need for other types of shielding effectiveness measurements to be performed on operational shielded C^3 facilities for two purposes: (1) initial certification of shielding effectiveness for a new shield; and (2) periodic or continual monitoring of the shielding effectiveness of a facility shield over the lifetime of the shield. For these two latter purposes, measurement procedures should be available which are:

- Relatively simple, so that they are readily adaptable to measurement operations "in the field";
- Capable of providing reproducible results, so that any changes in measured data can be identified as changes in shielding effectiveness;
- Non-interfering, so they can be performed either intermittently or continuously during C^3 facility operation without causing operational interference;
- Diagnostic, so that any shield defect can be located easily.

As pointed out in Section 2.5, suitable shielding measurement procedures are not available and cannot be developed either on small-scale models in the laboratory or on operational C^3 facilities. Consequently, it is appropriate that such procedures be developed on the test bed facility.

The test bed facility will be used for obtaining shielding data for shields with a wide variety of characteristics (e.g., different seam construction, different number of apertures, etc.), and with the interior of the facility first empty and then containing simulated equipment racks. These same experimental configurations can be used for trying and evaluating various simple test procedures intended for initial shield certification and lifetime performance monitoring. Furthermore, the internal fields will be mapped in detail to obtain the shielding data, and these results can be used for guiding the selection of candidate techniques for the desired simpler measurement procedures.

It is proposed here also that CW techniques would be used. Test equipment is simpler, measurement sensitivity is better and, by using only limited portions of the spectrum, interference to operational C^3 facilities can be avoided.

The major test considerations are:

- Frequencies to be used;
- Method(s) of exciting the shield;
- Type(s) and locations of sensors;
- Required excitation levels.

One possible method of exciting the shield is by current injection on the outer surface of the shield via appendages connected to appropriate portions of the shield, e.g., three pairs of diagonally opposite corners, with pairs switched alternately. Any procedures to be developed must consider the fact that shielding tests on an operational C^3 facility will be performed in the presence of the facility ground, which will tend to shunt to ground a substantial portion of any current injected onto the shield. The extent of this effect, of course, will depend on the nature of the ground (e.g., single point or multi-point).

Sensors to be tried would include a commercial $\dot{B}$ free-field sensor and a $\dot{D}$ free-field sensor, as well as various size wire loops and dipoles at different locations (see Section 3.2).

Eventually, use of discretely stepped frequency would probably be recommended to simplify synchronizing transmitter and receiver, avoiding interference to the C^3 instrumentation and other facilities, and switching of sensors and possibly matching networks.

Excitation levels will depend on sensor sensitivity and, in turn, on system bandwidth. Since only a few (perhaps 10) frequencies may be required and data is not required at a high rate, a very narrow bandwidth can be used to minimize the required levels of drive current.

3.4 INVESTIGATE EFFECTS OF SHIELD MAGNETIC SATURATION

As discussed in Section 2.6, some degree of magnetic saturation of a steel shield could be expected to occur for realistic EMP threats. Since magnetic saturation is a nonlinear phenomenon, its effects should be determined for the magnetic intensities and waveform durations ultimately of interest. Due to the difficulty of generating excitations at the threat level, both for radiated fields and for injected currents, it is proposed that the effects of saturation be investigated by a combination of experimental work and theoretical modeling.

The test bed facility should be used to determine the magnetic fields within the shielded enclosure for radiated pulse excitations of various levels, beginning at low levels where saturation is not encountered, and continuing progressively to higher values where at least partial saturation occurs.

The results should be correlated with analytical predictions based on present theories of saturation of an infinite flat plate and on measurements of shield surface current densities performed both during full-scale test bed investigations (Section 3.1) and supporting laboratory studies using a small-scale model (Section 4.1.2).

Since it may not be practical to perform saturation tests at the full threat level, the objectives of this phase of the work should be the development of an analytical approach to the problem, and experimental validation of that approach. Once the phenomenon is understood, it may be possible to predict the saturation behavior for other excitations, e.g., longer durations and greater amplitudes.

To the extent that saturation effects at the corners of the shield may be found to be important in lowering the performance of the enclosure, it may be possible to reduce this effect by using thicker steel in those regions.

SECTION 4

PROPOSED SUPPORTING TASKS

4.1 PERFORM SMALL-SCALE MODEL TESTS

The nature of the test bed facility experiments discussed in Section 3 is the measurement of external and internal surface currents on the shield, magnetic field measurements throughout the interior of the enclosure, and spot-checking of the interior electric fields. These surface currents and interior fields will depend strongly on the manner in which external currents are applied to the enclosure.

It is recommended that certain small-scale model laboratory tests be performed prior to performing the test bed facility measurements. The purpose of the small-scale model tests is to measure the distribution of the external surface currents on a small box-like metal enclosure for various radiated field and injected current excitations. The results will provide guidance for measurement on the larger-scale test bed facility.

Two types of small-scale model experiments are recommended:

1. Measurement of the redistribution of external shield surface currents for various facility grounding configurations.
2. Measurement of the external current distribution of the shield resulting from plane-wave excitation having various angles of incidence and polarization.

4.1.1 Investigation of Facility Grounding Configurations

The purpose of this test is to map the surface current density on the external surface of a shield for a variety of shield grounding configurations and earth conductivities. The shield would again be modeled by a metal box, perhaps 1 m x 1 m x 2 m, and the earth would be simulated by a sand base with conductivity appropriate to model earth conductivity. As shown in Figure 4, continuous-wave (CW) current would be injected onto the shield by a current source having one terminal connected to ground (the conductive sand). The shield grounding system could most simply consist of a single-point ground at the "entry plate", with the remainder of the shield isolated from ground except for the inevitable capacitance. Alternatively, a multipoint grounding system or a metal counterpoise could be used. It is estimated that perhaps six alternative grounding configurations and possibly three values of earth conductivity would be tested. Thus, if all combinations of parameters were tested, there would be a total of 18 tests.

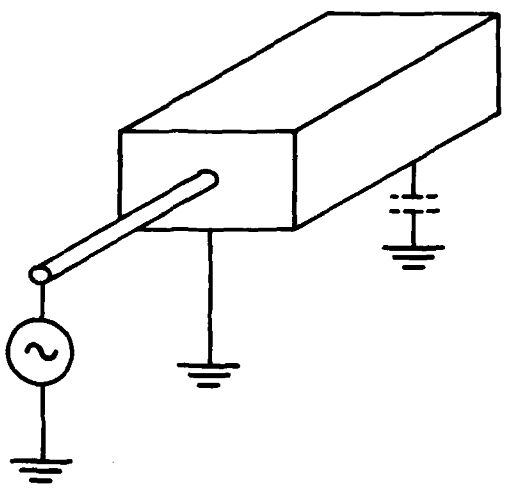


Figure 4. EXCITATION OF TEST BOX TO EVALUATE FACILITY GROUNDING CONFIGURATIONS

In this test, the quantities to be measured are the magnitude and the direction of surface current density versus frequency at each of approximately 25 points on each of the five shield surfaces.

A CW current source of approximately 5 amperes, RMS, swept over the frequency range from 10 kHz to 100 MHz would be desirable. Most likely, four sweep segments would be required -- one for each decade.

Again, a $\dot{J}$ sensor followed by an integrator would be used to measure the surface current density vector, J, at each surface point. Also, J in both orthogonal directions is required. The integrator output could be applied to an envelope detector, and the detector output applied to a chart recorder. Assuming measurements at 25 points per surface and five surfaces, data would be required at 125 points per test.

4.1.2 Radiated Test of Shield External Current Distribution

The purpose of the radiated coupling test is to determine the current distribution on the external surface of a shield illuminated by a plane-wave pulsed EMP type signal. A metal box, perhaps 1 m x 1 m x 2 m, plus a ground plane, would be emplaced in a parallel plate EMP simulator and tested under the following illumination and environmental conditions:

Vertical angle of incidence: 0^o; 45^o; 90^o
Horizontal angle of incidence: 0^o; 45^o
Polarization: Horizontal; Vertical
Ground Plane: Connected; Isolated.

A surface current ($\dot{J}$) sensor would be used to measure the current density at a grid-like array of points (between 25 and 100 points) on each of the five accessible faces of the metal box. The $\dot{J}$ sensor output would be converted to J either by sensor loading or with an integrator, and the J output would be displayed and photographed on an oscilloscope. Measurements over the box will show the extent of current concentration, i.e., at corners, and also any buildup along the length of the enclosure. Testing under the conditions listed above should show the worst-case situations.

If tests are performed under all combinations of conditions listed, there would be a total of 24 tests.

In order to approximate a plane wave incident on the metal box, a bounded wave simulator using strip transmission line is proposed. To accommodate a test box 1 m x 1 m x 2 m under the various proposed propagational conditions, a parallel-plate transmission line should have dimensions of at least 3 m wide by 2 m high by 4 m long. Threat-level excitation is not required. An incident magnetic field H = 10 A/m should be adequate; the corresponding electric field is E = 3.77 kV/m.

The test box 1 m x 1 m x 2 m can be considered to be a small-scale model of a shielded facility that may realistically have dimensions approximately 10 times that size. Therefore, the test waveform spectrum used with the small box should correspondingly be scaled upward in frequency by a factor of ten in order to obtain properly scaled time waveforms of the surface currents. If a threat pulse has rise and fall times of 10 nanoseconds and one microsecond, respectively, the test simulator should provide rise and fall times of one nanosecond and 100 nanoseconds, respectively, for 10:1 scaling. The test waveform should be repetitive to permit its observation on a sampling oscilloscope.

The surface current sensor could be similar to the $\dot{J}$ sensor, EG&G Model MGL, perhaps Type S7 with an equivalent surface area of 10^{-4} m^2, and physical dimensions of 10.4 cm long by 5.6 cm wide. In addition, a passive integrator would be used for providing J. Two sets of data would be required -- one for each of the two orthogonal directions on the surface.

A wideband data link would be required between the integrator output and the input of a wideband sampling oscilloscope located remotely and shielded from the test fields. An oscillogram would provide a permanent visual recording of the waveform. It is anticipated that most of the data review would consist of visual examination of the oscillograms, with possibly a limited amount of digital processing of selected waveforms.

In order to reduce the total test time for obtaining waveform data over five surfaces of the box, several sensor, data link, and oscilloscope channels should be used in parallel. Perhaps five channels could be used, with one sensor on each of the five surfaces.

4.2 DEVELOP SIMPLE ANALYTICAL MODELS

The test bed facility, while being flexible enough to provide shielding data for a wide variety of shield construction parameters and designs, will still provide measured data on only a limited set of enclosures simulating C^3 facility shields. It is intended that the data measured for the finite number of shield configurations will provide a basis for the design of shields suitable for operational C^3 facilities for a variety of conditions. Thus, the measured data will need to be interpreted and extrapolated to provide guidelines useful for designing the specific C^3 facility shields required. A set of relatively simple analytical models is recommended as the means for accomplishing this data interpretation and extrapolation. Specifically, it is proposed that analytical models be developed which relate to:

- Shield design and internal fields;
- Shield design and internal coupling;
- Simplified procedures for measuring shielding effectiveness;
- Effects of shield magnetic saturation.

The first set of models would analytically relate the dominant shield parameters to the field strengths and/or induced voltages within the enclosure. The models can be developed by an iterative process of assuming a model, attempting to validate it by means of the experimental data, refining the model, etc., until good agreement is obtained. This requires that the two efforts be conducted in parallel. The analytical effort may impose or define additional parameters or measurements to define the various interactions of parameters. Thus, one purpose of the models is to interpret and extrapolate the measured parametric shielding data for the internal fields.

At the present time a number of models already exist. For example, models for attenuation for materials based on skin depth criteria exist, and these have been fairly well validated. In other cases, however, models such as those which have been developed for single or multiport apertures identify the shielding effectiveness only in the near vicinity of the aperture. They do not relate directly to the overall degradation of the shielding effectiveness of a shielded facility. This is due to the fact that there is an interaction of the aperture characteristics with the structure geometry. Parametric data defining this relationship, in the form of an analytical model, would be desirable.

In Section 3.2 experimental investigations using radiated pulses are discussed for relating shield design (and internal fields) to internal cable coupling. Simple analytical models should be proposed and tested for relating internal cable coupling to shield design parameters. For example, use of the magnetic polarizability for a leaky seam has been proposed[9] for calculating the voltage induced in a long wire within an enclosure. This appears to be one very useful model for which validation would be worthwhile. Another may relate to penetrants, or to corner effects.

Another purpose of the models would be to support the development of suitable simplified shielding measurement procedures. Here the emphasis would be on models which allow the approximate computation of magnitudes and location of maximum field strengths and correlation of such field strengths with maximum voltages or currents induced in test receiving loops or test wires.

The fourth area in which analytical modeling would be desirable is in relation to magnetic saturation of a steel shield. Here, the investigation should relate previously available analyses for an infinite planar sheet, measured shield surface currents, and shield interior magnetic fields for several levels of excitation (Section 3.4). Saturation most likely will take place at edges, corners, points of entry, etc., where large currents are concentrated. At these localized regions we can expect degradation to occur. A simple way to view this in terms of shield design parameters, overall shielding effectiveness, etc., is to consider these saturation regions as virtual apertures, i.e., regions where, in effect, parts of the shield "disappear". Thus, a sharp change in shielding effectiveness results. It is reasonable to expect that the saturation area will increase as amplitude of the excitation increases. If so, the effect will be to widen these virtual apertures.

As shown in Figure 5, the analytical models would:

- Interpret test bed facility data;
- Guide test bed facility experiments;
- Provide shield design procedures and simplified shielding effectiveness (S.E.) measurement procedures.

Over the long term, shielding effectiveness measurements on shielded C^3 facilities will provide additional data which can be used to refine the analytical models, if warranted.

4.3 PROPOSE DEFINITIONS OF SHIELDING EFFECTIVENESS

The purpose of this analytical task is to propose and evaluate definitions of shielding effectiveness intended to be meaningful and useful in a practical way for a variety of situations. The definitions should be applicable to the following cases:

Threats

Incident radiated fields
Currents on penetrants, injected onto the shield

Measurement

Fields in empty enclosure
Voltages and currents induced in equipment cables
Simplified shielding effectiveness tests.

Assuming that the shielding effectiveness would be defined as the ratio of an electromagnetic quantity outside the shield to an electromagnetic quantity inside the shield, some of the possibilities include:

External field or current/internal field; and

External field or current/internal voltage or current;

normalized per unit length or area of circuit.

The definitions must be valid under various conditions related to: direction of incidence, earth reflection, configuration of penetrants, grounding system, corner effects, and saturation. Thus, while the definition of shielding effectiveness applies to a shielded enclosure, it must apply to that enclosure under a wide variety of conditions, as it is under these conditions that the enclosure will be used and tested.

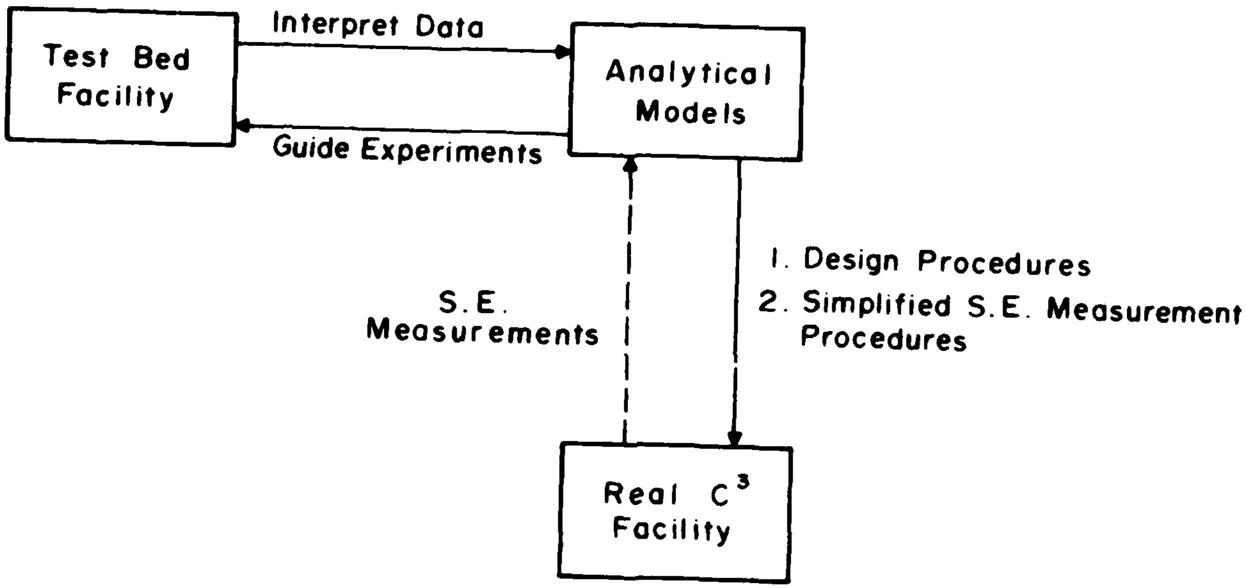


Figure 5. INTERACTION AMONG ANALYTICAL MODELS, TEST BED MEASUREMENTS, AND DESIGN AND TEST OF SHIELDED C^3 FACILITIES

SECTION 5

CONCLUSIONS AND RECOMMENDATIONS

A Shielded Enclosure Test Bed Facility is needed in order to provide the following types of information relative to the design and testing of shields for shielded C^3 facilities:

- Relationships between shield design parameters and the magnitudes and distributions of fields within the shielded enclosure;
- A meaningful definition of shielding effectiveness based on the fields within the enclosure;
- Relationships between shield design parameters and internal coupling to equipment racks and interconnecting cables;
- Relatively simple but meaningful procedures for measuring the shielding effectiveness of an enclosure;
- Effects of shield magnetic saturation on shielding effectiveness.

The Test Bed Facility should have the capability to provide a shielded enclosure approximately 10 ft. high x 20 ft. wide x 50 ft. long with a variety of shield design parameters such as shield materials and thickness and seam characteristics. It should have the capability for both CW injected current excitation and radiated pulse excitation, and appropriate electromagnetic sensors and signal processing equipment for data collection.

The following test bed facility tests are recommended:

- Mapping of exterior and interior shield surface current densities and internal fields, using CW current injected onto the shield;
- Measurement of internal cable coupling for shield excitation by CW injected current and by pulse radiation;
- Development of simplified procedures for measuring shielding effectiveness, using CW techniques;
- Investigation of effects of shield magnetic saturation, using pulse radiation.

In addition to the test bed facility investigations, the following supporting tasks are recommended:

- Small-scale model tests in a laboratory to determine external surface currents on a shield and to determine the effect of various facility grounding configurations;

- Development of simple analytical models related to shield design and internal fields and internal coupling, simplified procedures for measuring shielding effectiveness, and effects of shield magnetic saturation;

- Evaluation of possible definitions of shielding effectiveness applicable to a wide variety of conditions.

SECTION 6

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ATTN: Code F30
ATTN: Code F32

Naval Telecommunications Command
ATTN: Deputy Director Systems

Office of Naval Research
ATTN: Code 715

Office of the Chief of Naval Operations
ATTN: OP 98
ATTN: OP 94

Strategic Systems Project Office
Department of the Navy
ATTN: NSP-43

DEPARTMENT OF THE AIR FORCE

Air Force Communications Service
ATTN: XP

Air Force Geophysics Lab
ATTN: SULL

Air Force Security Service
ATTN: XRX

Air Force Weapons Lab
Air Force Systems Command
ATTN: DYC
ATTN: SUL
ATTN: NTO

ACofS Studies & Analyses
Department of the Air Force
ATTN: AF/SA

Ballistic Missile Office
Air Force Systems Command
ATTN: MNRTE

Operations Plans & Readiness
Department of the Air Force
ATTN: AFXOK

Research, Development & Acq
Department of the Air Force
ATTN: AFRDQ

Foreign Technology Division
Air Force Systems Command
ATTN: NIIS Library

Rome Air Development Center
Air Force Systems Command
ATTN: TSLD

DEPARTMENT OF THE AIR FORCE (Continued)

Headquarters Space Division
Air Force Systems Command
ATTN: SKF

Commander in Chief
Pacific Air Forces
ATTN: Communications Electronics

Strategic Air Command
Department of the Air Force
ATTN: NRI-STINFO Library
ATTN: XPFS

OTHER GOVERNMENT AGENCIES

Federal Emergency Management Agency
ATTN: Plans & Operations (EO)

DEPARTMENT OF DEFENSE CONTRACTORS

American Telephone & Telegraph Co
ATTN: M. Gray for W. Edwards

BDM Corp
ATTN: L. Jacobs

Boeing Company
ATTN: V. Jones
2 cy ATTN: H. Hendrickson

Computer Sciences Corp
ATTN: H. Blank

ESL, Inc
ATTN: J. Marshall

General Electric Company—TEMPO
ATTN: DASIAC

Sylvania Systems Group
ATTN: M. Cross
ATTN: E. Motchok

Institute for Defense Analyses
ATTN: Classified Library

IRT Corp
ATTN: R. Wheeler
ATTN: L. Duncan
ATTN: D. Swift

R & D Associates
ATTN: R. Schaefer
ATTN: C. MacDonald
ATTN: B. Gage
ATTN: W. Graham, Jr
ATTN: P. Haas

R & D Associates
ATTN: J. Bombardt

SRI International
ATTN: A. Whitson
ATTN: G. Carpenter

Georgia Institute of Technology
ATTN: H. Denny

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